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Procedia Engineering 15 (2011) 521 – 525
Procedia Engineering
www.elsevier.com/locate/procedia

Semi-active Control of High-speed Trains Based on Fuzzy PID Control

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Abstract

Establishing the 1/4 vehicle mathematical model based on the nonlinear model of semi-active suspension system for high speed trains, the PID controller and the fuzzy adaptive PID controller were set up respectively on the semi-active suspension system, and the simulations of the high-speed train were carried out under the condition of passive suspension and the semi-active suspension based on the algorithm of the fuzzy adaptive PID control to compare the stability of the high-speed vehicle under these two cases. Results of the simulation show that: the stability and the comfortableness of the high-speed can be improved effectively by using the semi-active suspension with fuzzy adaptive PID control method.

Keywords: high-speed train; fuzzy control; PID; semi-active.

0 Introduction

Traditional passive suspension cannot meet the needs of the development of high-speed train with the accelerating of the railway speed. The semi-active suspension of vehicles uses the damping components that can be controlled and the closed loop control system, which can regulate the damping force according to the feedback signals generated by the lateral acceleration of the car body, so that the damping suspension stay in the best condition and improve the stability of high-speed train. Therefore, well-designed semi-active suspension system is an effective approach to decrease the vibration of the vehicle and improve the vehicle's stability.

Semi-active suspension system is a nonlinear system, and there are some limitations for the traditional control strategy used in nonlinear system. Adaptive control uses the modern control theory, identifying the parameters of object online, changing the control strategy real-time to keep the quality indicator of the control system stay in the best range. Using the basic theory and methods of the fuzzy mathematics, the regular conditions and operations can be expressed by the fuzzy sets. Storing the regulation and the information related (such as the initial PID parameters, etc.) into the computer as knowledge. And then computer can adjust the PID parameter to the optimum by using fuzzy reasoning according to the actual response of the control system, which is the fuzzy adaptive PID control.

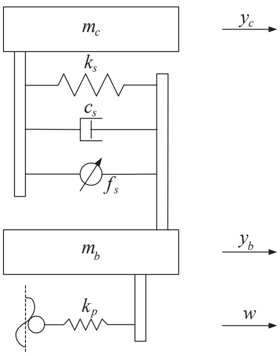


Fig.1 1/4 Vehicle model

1 The dynamic model of high-speed train with semi-active suspension system

Figure 1 shows the 1/4 high-speed vehicle model with semi-active suspension system, including a 1/4 body and a 1/2 bogie. As the main assessment of railway vehicles' stability is the lateral

doi:10.1016/j.proeng.2011.08.099

acceleration of the body, and in order to simplify the model, the vertical stiffness and vertical damping coefficient of the primary and secondary suspension have been ignored. Accounting the sliding movement of body and bogie only, excluding their shaking head and roll movement.

In the Figure 1, m_c is the 1/4 body mass, y_c is the lateral displacement of the body, k_s is the lateral stiffness of the secondary suspension, c_s is the lateral damping of the secondary suspension, f_s is the semi-active damping components which provides variable damping force, m_b is half of the bogie mass, y_b is the lateral displacement of the bogie, k_p is the lateral stiffness of the primary suspension, w is the amount of track irregularity. The secondary damping of the vehicle system is neglected.

The arrow direction of y_c , y_b and w oriented is the positive, the equations can be established as follows according to Newton's second law:

$$\mathrm{m}_b \ddot{y}_b = k_p(w - y_b) - k_s(y_b - y_c) - c_s(\dot{y}_b - \dot{y}_c) - f_s \tag{1}$$

$$\mathrm{m}_c \ddot{y}_c = k_s(y_b - y_c) + c_s(\dot{y}_b - \dot{y}_c) + f_s \tag{2}$$

Selecting the state vector $\vec{x} = [x_1 x_2 x_3 x_4]^T$, in the formula $x_1 = y_c$, $x_2 = \dot{y}_c$, $x_3 = y_b$, $x_4 = \dot{y}_b$, $\vec{x} = [\dot{x}_1 \dot{x}_2 \dot{x}_3 \dot{x}_4]^T = [\dot{\mathrm{y}}_c \ddot{y}_c \dot{y}_b \ddot{y}_b]^T$, assuming $u = f_s$, then we can get the state space expression of the 1/4 vehicle model:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k_s}{m_c} & -\dfrac{c_s}{m_c} & \dfrac{k_s}{m_c} & \dfrac{c_s}{m_c} \\ 0 & 0 & 0 & 1 \\ \dfrac{k_s}{m_b} & \dfrac{c_s}{m_b} & \dfrac{-k_s - k_p}{m_b} & -\dfrac{c_s}{m_b} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{k_p}{m_b} \end{bmatrix} w + \begin{bmatrix} 0 \\ \dfrac{1}{m_c} \\ 0 \\ -\dfrac{1}{m_b} \end{bmatrix} u \tag{3}$$

$$y = [0100][x_1 x_2 x_3 x_4]^T \tag{4}$$

2 PID control strategy based on adaptive fuzz

To achieve better PID control effect, it must coordinate the control function of the proportion, integration and differential, that is to adjust the three parameters to achieve the best control effect. In the continuous time analog controller, the ideal characteristics of the proportion, integration and differential can be expressed by the formula (5):

$$\Delta u(t) = k(e(t) + \frac{1}{T_l}\int e(t)dt + T_D \frac{de(t)}{dt}) \tag{5}$$

In the formula (5), K is the proportional gain; T_l is the integration time; T_D is the differential time; $e(t)$ is the control error; $\Delta u(t)$ is the output of the controller namely the control amount. Setting the proportion coefficient $k_p = K$, integral coefficient $k_i = K/T_l$, differential coefficient $k_d = KT_D$, substituting into the formula(5),

$$\Delta u(t) = k_p e(t) + k_i \int e(t)dt + k_D \frac{de(t)}{dt} \tag{6}$$

Error e and error change ec are considered as the input of the adaptive fuzzy PID controller, so e and ec can vary with the change of the PID parameter self-tuning in different moments. Fuzzy control rules to modify parameters of the PID online will form the adaptive fuzzy PID controller, the structure can be seen in Figure 2.

Fuzzy PID parameters self-tuning is to identify the fuzzy relationship between three parameters of the PID and e, ec, testing e and ec in the operation constantly, modifying the three parameters online according to the fuzzy control theory to meet the different requirements to the control parameters, to make sure that the controlled object has a good dynamic and static performance.

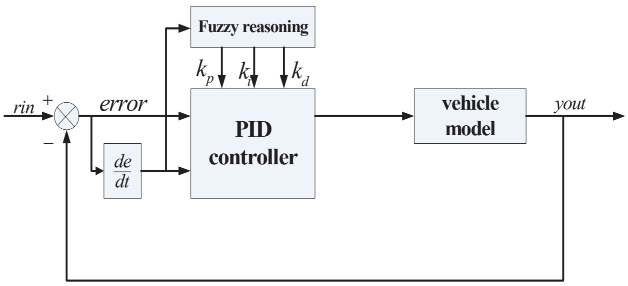


Fig.2 Adaptive fuzzy PID controller structure

1) Domain of fuzzy sets of error e, error change ec and control amount u are defined as follows:

The fuzzy sets of e, ec and u are all the same: $\{NB, NM, NS, Z, PS, PM, PB\}$, these elements stand for negative big, negative middle , negative small, zero, positive small, positive middle, positive big respectively. The domain of the e, ec all are: $\{-5,-4,-3,-2,-1,0,1,2,3,4,5\}$. The domain of u is $\{-4.5,-3,-1,0,1,3,4,5\}$.

2) Establishing the fuzzy control rule

Reasoning based on human intuition, using the fuzzy control rules to eliminate systematic errors according to the error and its change trend, and then constituting the fuzzy model of controlled process described by numbers of fuzzy control statements.

3) Determining the assignment tables of the fuzzy variables

After determining the fuzzy domain of the fuzzy variable error e, error change ec and control amount u, shall determine function that the fuzzy linguistic variables subjected to, assigning variable , determining the membership of the fuzzy linguistic variables within the domain.

4) Founding the fuzzy control tables

Fuzzy control rules described above can be represented by the fuzzy control table, a total of 49 fuzzy rules, the relationship of each fuzzy statement is 'or', u_1 can be calculated from the control rules determined by the first statement. Similarly, u_1 ,…, u_{49} can be obtained from the remaining statements. And the control amount should be the fuzzy sets u, which can be expressed by formula (7):

$$u = u_1 + u_2 + \ldots + u_{49} \tag{7}$$

The key of the fuzzy control design is the establishment of appropriate fuzzy sheet, to get the fuzzy control table direct at the three parameters k_p, k_i, k_d.

5) Defuzzification

According to the fuzzy control amount calculated from above, using the maximum membership method to change the control amount from the fuzzy quantity into a precise volume. To obtain accurate control amount would require the fuzzy method can express the output results of the fuzzy membership function. For each elements of the domain $x_i(i=1,2,...,n)$, using the weighted average method as the weighted factor of the fuzzy set membership $\mu(i)$ to be judged, that is to take the product $x_i\mu(i)$,and then calculate the sum $\sum_{i=1}^{n} x_i\mu(i)$ and the average for the membership x_0 , namely:

$$x_0 = \sum_{i=1}^{n} x_i\mu(i) \Big/ \sum_{i=1}^{n} \mu(i) \tag{8}$$

Average x_0 is the outcome for the fuzzy sets using weighted average method. Finally, the output scaling factor is multiplied to x_0 to meet the control requirements, and then obtain the actual value of the control amount.

During the course of online operation, the control system complete the online self-tuning of PID parameters through the processing of outcome controlled by the fuzzy logic rules, looking-up the table and computing. The workflow is shown in Figure 3.

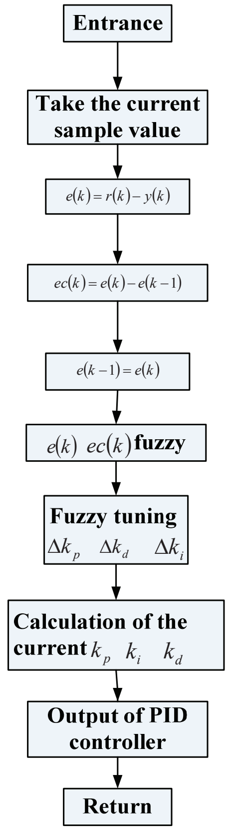


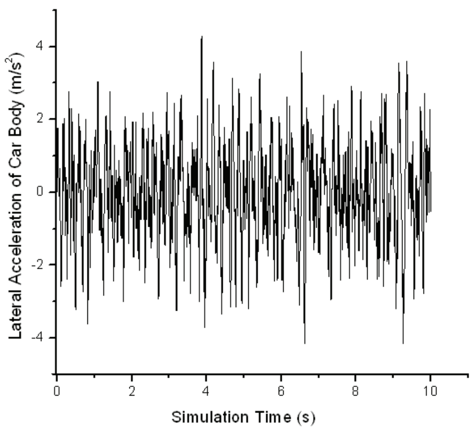
Fig.3 Self-turning workflow online

3 Simulation results analysis

In equation (1) (2), $m_c=10000kg$, $m_b=2000kg$, $k_p=2MN/m$, $k_s=180KN/m$, $c_s=0$ when the suspension is semi-active suspension, while $c_s=50kNs/m$ when it is passive suspension. Ignoring the mass of the wheel, the wheel can be seen as fixed in the amount of track irregularities input. The constant velocity for the 1/4 vehicle model is $c_s=360km/h$, length of track irregularity spectrum is 1000m, the simulation time is 10s. Using the white noise signal as the input of the track irregularity w and the output should be the lateral acceleration of high-speed train $\ddot{y}_c$.

Figure 4 shows the curve that the body lateral acceleration of the 1/4 high-speed vehicle model with passive suspension system change with the simulation time, Figure 5 is the curve vary with the simulation time of 1/4 semi-active suspension vehicle body's lateral acceleration based on fuzzy adaptive tuning PID control algorithm.

From the simulation results of the high-speed train with passive suspension and semi-active suspension system respectively, as shown in Fig 4 and Fig 5, obviously it can be seen: maximum lateral acceleration has exceed $4m/s^2$ in the 1/4 high-train vehicle model with semi-active suspension, while the lateral acceleration is only about $2m/s^2$ when use the semi-active suspension with fuzzy adaptive PID control. Then the conclusion can be obtained: high-speed trains based on semi-active suspension system with fuzzy adaptive PID control can effectively reduce the lateral acceleration, which can improve vehicle stability and comfortableness.



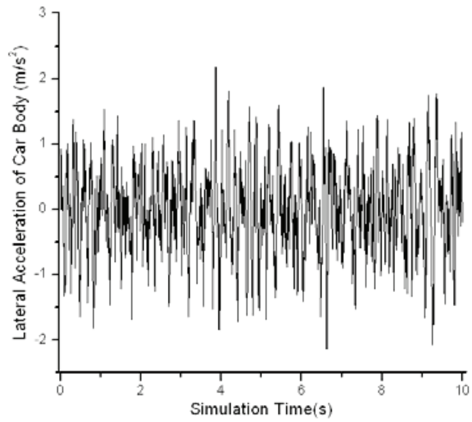


Fig.4 curve vary with the simulation time of lateral acceleration with passive suspension

Fig.5 curve vary with the simulation time of the the lateral acceleration with semi-active suspension

4 Conclusion

By establishing 1/4 high-speed train vehicle model with semi-active suspension based on fuzzy adaptive PID control, simulating the model under the two different cases, passive suspension and semi-active suspension system based on fuzzy adaptive PID control, to compare their lateral acceleration, and thus compare the running smoothness. By comparing the two results, it can be concluded: high-speed trains based on semi-active suspension system with fuzzy adaptive PID control can effectively reduce the lateral acceleration, which can improve vehicle stability and comfortableness.

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